Canyons and slides on the continental slope seaward of shallow banks, Labrador margin, eastern Canada

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The ~ 200 km-wide Labrador continental shelf consists of a series of shallow banks and intervening cross-shelf troughs (Fig. 1b). Glacial reconstructions suggest that the banks were occupied by slow-flowing ice and the troughs by ice-streams during several Quaternary glaciations (Dyke *et al*. 2002; Josenhans *et al*. 1986; Margold *et al*. 2015). On the continental slope offshore of the Makkovik Bank - southern Hopedale Saddle region, several submarine canyons and interfluves with numerous sediment destabilisation features are visible in multibeam data (Fig. 1a).

Description

The continental shelf break between Makkovik Bank and Nain Bank occurs at about 300 m water depth (Fig. 1b). The southeast to northwest orientated continental slope extends to ~2200 m. Slope gradients between 1000 m and 1400 m are about 5°–6°, whereas between 1400 m and 2000 m they have a modal value of 3°. Slope gradients below 2000 m are generally less than 2°. Numerous deeply incised submarine canyons occur along the continental slope (Fig. 1a, c). The canyons are bounded by interfluves that have sharp crests. The spacing of interfluve crests, measured in their upper reaches, ranges between 1 and just over 3 km, with a modal spacing of ~ 2 km (Fig. 1a, g). Canyon cross-profiles are variable in shape with distance down the continental slope. The canyons themselves are 'V'-shaped in their upper reaches (Fig. 1c, g), becoming more flat-bottomed down-valley (Fig. 1h). The change in shape of the valley cross-profiles occurs at approximately 1400 m, where there is a decrease in the continental-slope gradient (Fig. 1c). Canyon flanks generally slope between 30° and 35°, reaching over 40° in places (Fig. 1g). The largest height difference between interfluve crests and valley bottoms is 465 m.

Three types of smaller-scale mass-transport features are visible in multibeam and sometimes sub-bottom profiler data (Fig. 1a, e): (i) slides initiated on the steeper upper continental slope; (ii) smaller canyon-flank slides, on the upper- and mid-slope; and (iii) secondary lower-valley slides on the lower slope (Fig. 1a, e). The arcuate headwall scarps of the two prominent slides on the upper slope ('lss' and 'ss' in Fig. 1a) have upper rim depths of ~1200 m and 800 m and are ~ 4 km and 1 km wide, respectively. Both these arcuate headwall scarps show maximum relief of ~ 100 m. The steepest scarp-headwall gradients are 32° and 30° for '1ss' and 'ss', respectively. These headwall scarps are visible in seismic data where evidence for slide activity also exists further upslope (Fig. 1e)

The occurrence of relatively small canyon-flank slides is indicated by arcuate headwall scarps (Fig. 1a). However, no evidence of debris-flow deposits or lobes from valley-flank mass-transport is evident on the valley bottom directly downslope of these canyon-flank slides. Debris transported from the valley flanks may be carried further downslope in the main canyons or contribute to valley fill without any expression.due to topographic constraints such as the narrow canyon bottoms.

Secondary mid-valley slides occur between 15 and 20 kilometres downslope from the canyon headwalls, in water depths ranging from ~ 1800 to 2000 m for the slide headwalls. (Fig. 1a). The headwall scars situated lowermost down the continental slope are generally narrower and slightly steeper than those up-slope in shallower water depths, showing maximum gradients of about 36° and over 150 m of relief (Fig. 1d). The mid-valley slides have dissected pre-existing sediment lobes during multiple mass-transport events (Fig. 1a).

Interpretation

The incised canyons, smaller-scale slides and sediment lobes, recognised in swath-bathymetric and sub-bottom profiler data along the continental slope offshore from the southern part of Hopedale Saddle and Makkovik Bank (Fig. 1a-e), represent a downslope developmental continuum as the dominant process shifts from erosion to deposition. Erosion on the upper continental slope formed the canyons through which sediment was transported down-valley and deposited either as valley-fill or transported beyond valley mouths. This pattern was repeated as sediment in the mid- and lower canyons underwent subsequent failure in the form of secondary slides (Fig. 1a).

The Labrador shelf is part of a passive margin that has been shaped by Quaternary glacial episodes (Josenhans *et al*. 1986). The geology along most of the Hopedale Saddle cross-shelf trough consists of an upper till unit of low shear strength overlain by ice-proximal and ice-distal glacimarine silts (Josenhans *et al.* 1986). However, an older, consolidated and bouldery till crops out along the shelf edge in the southern part of the Hopedale Saddle and northernmost Makkovik Bank, immediately landward of the study area (Josenhans *et al.* 1986). The distribution of these till units indicates that an ice stream flowed through Hopedale Saddle and turned to the northeast on the outer shelf. The study area, seaward of the southern part of the Hopedale Saddle and Makkovik Bank area, is therefore interpreted as lying in an area of relatively low sediment delivery from slow-flowing ice to the shelf edge (Ottesen & Dowdeswell 2009). This part of the Labrador margin appears to have been an inter-ice stream area during at least the last glacial period. Erosional processes therefore dominate the continental slope here, accounting for the incised submarine canyons (e.g. Taylor *et al.* 2000).

The slower rate of full-glacial sediment delivery to the slope from Makkovik Bank relative to an adjacent ice stream is reflected in the changing physiography along the continental margin from southeast to northwest in the Makkovik Bank-Hopedale Saddle region (Fig. 1b). The southeast part, represented in Figure 1a, consists primarily of canyons with increasing amounts of valley fill to the northwest (Fig. 1a). The central Hopedale Saddle, beyond our imagery further to the northwest, displays a network of anastomosing submarine channels and their associated sediment fill, inferred to have formed in a region of more rapid sediment delivery beyond a Quaternary ice stream (Dowdeswell *et al*. 2016). Canyon development is probably limited on glacier-influenced high-latitude margins more generally because of relatively high rates of sediment delivery to, and associated progradation of, much of the shelf edge during successive Quaternary glaciations.

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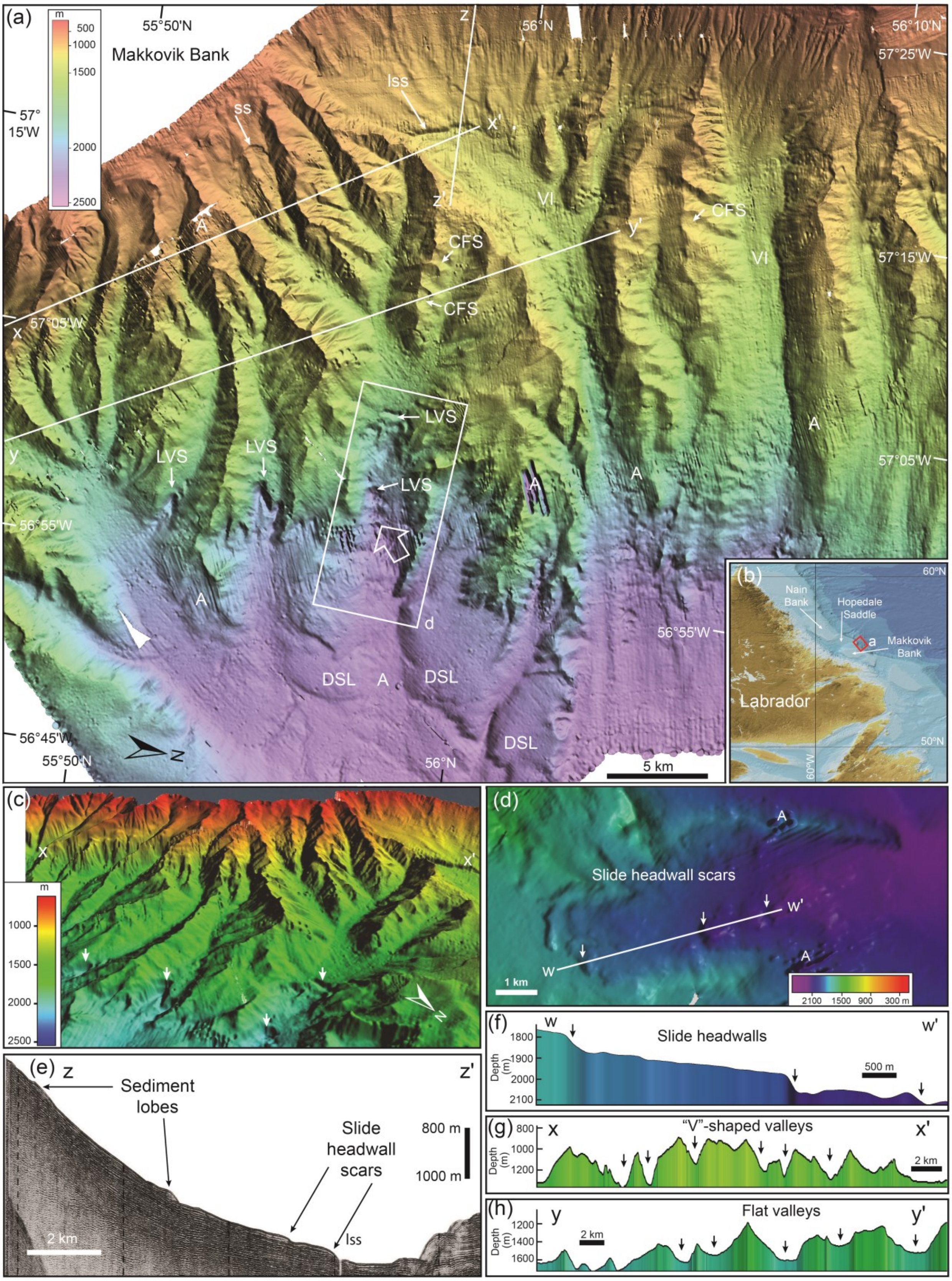

Fig.1. (a) Multibeam swath-bathymetric data from the continental slope, offshore from the southern Hopedale Saddle – Makkovik Bank area, Labrador margin, showing canyons and interfluves with superimposed slides. Two slide-scars are labelled "lss" (large slide-scar) and "ss" (slide-scar). LVS is 'lower-valley slides;' CFS is 'canyon-flank slides;' DSL is 'dissected sediment lobes;' and A is 'artefacts.' Hollow arrow marks panel (c) viewpoint. Acquisition systems Kongsberg Simrad EM300 and EM 302. Frequency 30 kHz. Grid-cell size 10 m. (b) Location of study area (red box; map from GEBCO_08). (c) Oblique view of the continental slope looking southwest. Arrows correspond to the four lower-valley slides shown in panel (a). (d) Bathymetry of a lower-valley slide showing headwall scars. The colour bar shown applies to panels d, f, g and h. (e) Seismic profile showing evidence of several mass transport events. The slide headwall scar "lss" is shown on (a). Acquisition system Knudsen K320R sub-bottom profiler. Frequency 3.5 kHz. VE x 7.6. (f) Colour-shaded profile along the lower-valley slide shown in (d). Slide headwalls show over-deepened profiles. VE x 3.0. (g) Cross-profile of the canyons above 1400 m water depth showing their largely 'V'-shaped form. VE x 6.8. (h) Cross-profile of the canyons below 1400 m water depth showing the broader canyon floors. VE x 7.4.

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